Lecture III

☞ TESTING NEUTRINO PHYSICS AT LHC AND OTHER EXPERIMENTS

LHC Physics from the Neutrinos

☞ While high scale seesaw is most appealing, it is hard to test it directly by experiments !!

☞ Alternative lower seesaw scale is quite conceivable and have been considered and have direct LHC signatures!!

- TeV scale seesaw and left-right symmetry;

☞ They lead to physics motivated by neutrinos that can be seen at LHC ?

Three kinds of neutrino related LHC signals

- **Possibility of Low Seesaw scale- TeV scale W_R, Z', new Higgs etc.**

- **Sub-TeV scale doubly charged Higgs bosons in intermediate seesaw models**

- **Sparticle spectrum shift in high scale seesaw models.**

Low Scale Parity Restoration and Left-right models

☞ Details

➢ Gauge group $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

➢ Matter: $SU(2)_L$ Doublets: $Q_L \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix}$; $\psi_L \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$;
$SU(2)_R$ doublets: $Q_R \equiv \begin{pmatrix} u_R \\ d_R \end{pmatrix}$;$\psi_R \equiv \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$

Higgs: $\phi(2,2,0) \equiv \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}$;
$\Delta_R(1,3,+2) \equiv \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$

➢ $\mathcal{L}_Y = h_u \bar{Q}_L \phi Q_R + h_d \bar{Q}_L \tilde{\phi} Q_R + h_e \bar{\psi}_L \tilde{\phi} \psi_R + h.c.$
$+ f(\psi_R \psi_R \Delta_R + L \leftrightarrow R)$

Fermion masses

☞ **Masses arise from symmetry breaking**

➢ $< \phi^0 >= \begin{pmatrix} \kappa & 0 \\ 0 & \kappa' \end{pmatrix}$ and $< \Delta^0_R >= v_R$

➢ $< \phi >$ gives masses to quarks and charged leptons only

➢ $m_\nu \neq 0$ arises from the seesaw matrix (coming up).

Limits on W_R mass

☞ **No limit from beta and muon decays if ν_R is heavy and Majorana !!**

Why ? New process mediated by W_R is :
$n \rightarrow p + e + \nu_R$; **but nu_R is heavy - so this does not occur.**

Indirect effects:
Limit comes from $K_L - K_S$ mass difference, ϵ_K and d_n, all of which get new contributions from W_R sector; these limits are based on assumptions and can be avoided ! :

Bottom-line: One should search actively for TeV scale W_R and Z' in both LHC and possible ILC.

Collider signature of W_R production with Majorana right handed neutrino

☞ $\sigma_{pp\to W_R \to lN} \sim$ **pb at** $M_{W_R} \sim 800$ **GeV;**

Distinguishing signal- $pp \to jj\mu^-\mu^- + X$ **from RH Majorana neutrino decay.**
Present collider limits from D0 and CDF collaborations: $M_{W_R} \geq 720$ **GeV for the two jet two lepton mode.**

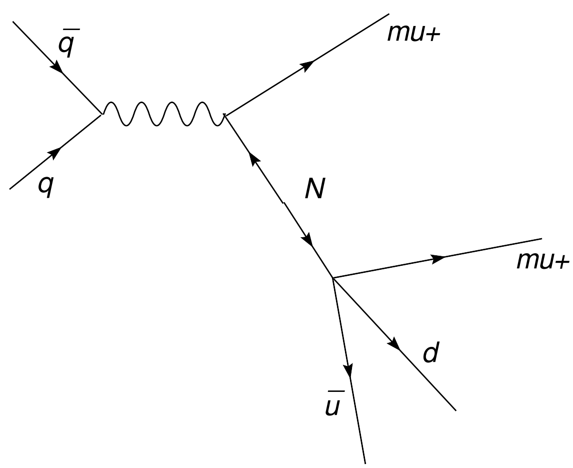
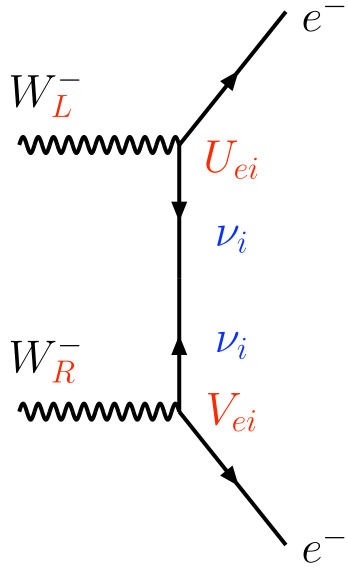


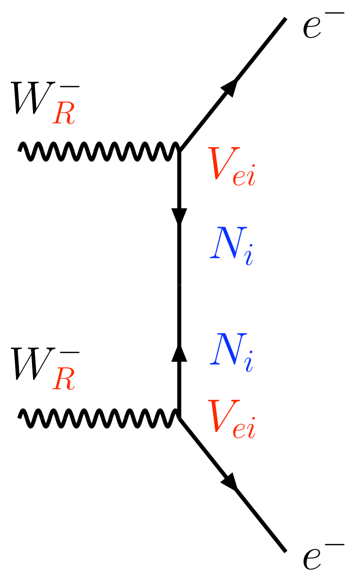
Figure 17: like sign dileptons with two jets and no missing energy is a signature of W_R production

New contribution to neutrinoless double beta decay



☞ **Bound on** M_R**:** $M_{W_R} \geq 1.3\ TeV \left(\frac{M_N}{1\ TeV}\right)^{-1/4}$

☞ **Usual nuclear matrix element uncertainty makes this bound reliable only within a factor of** ~ 2 **or so.**



LFV in TeV scale seesaw models

☞ **One loop diagram mediated by W_R and M_R:**

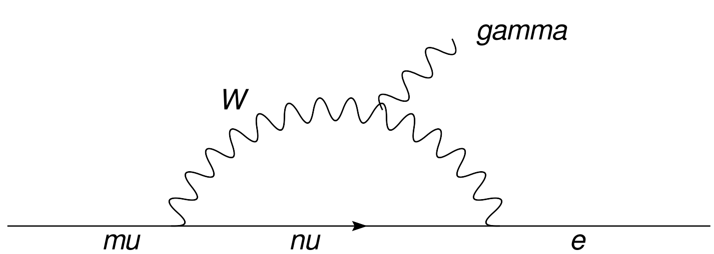


Figure 18: $\mu \to e + \gamma$ in non-SUSY nu-SM with low scale M_R

$$A(\mu \to e + \gamma) \simeq \frac{eG_F m_\mu m_e m^2_{N_R}}{\pi^2 m^2_{W_R}} \mu_B$$

Leads to $B(\mu \to e + \gamma) \sim \alpha \left(\frac{M_{W_L}}{M_{W_R}}\right)^4 \left(\frac{M_N}{M_{W_R}}\right)^4 \sim 10^{-11}$ **for** $M_{W_R} \sim 3.2$ **TeV and** $M_N \sim M_{W_R} \sim 1/3$

Low W_R at LHC

☞ $\sigma_{pp\to W_R\to N}\sim$ **picobarn for** $M_{W_R}\sim$ **TeV; it goes down as** M_{W_R} **increases;** 10^{-4} **pb for 5 TeV mass.**

LHC search limit 5-6 TeV; Collot et al; ATLAS study group; few events in a year.

Light doubly charged Higgs Bosons

☞ **A clear difference between SM, MSSM and LR sym. models is the presence of doubly charged Higgs bosons;**

They can be light (~ 100 GeV) if W_R scale is low;

They can also be low if Seesaw scale is 10^{11} GeV but there is supersymmetry.

So one should look for them in colliders !!

☞ **Decay modes: $\Delta^{++} \rightarrow e^+e^+, \mu^+\mu^+, e^+\mu^+$;**

Bounds from OPAL, CDF, DO searches:
$M_{\Delta^{++}} \geq 133, 136, 115$ **GeV's for different modes.**

☞ **Constraints on couplings**

➢ Leads to $\mu^+e^- \leftrightarrow \mu^-e^+$ oscillation:
PSI expt. has limit $M_{\mu^+e^- \leftrightarrow \mu^-e^+} \leq G_F \times 10^{-3}$
$\rightarrow \frac{f_{ee}f_{\mu\mu}}{M^2_{++}} \leq 10^{-8}$ GeV.

➢ $(g-2)$ of muon $f^2_{\mu\mu}\frac{m^2_\mu}{M^2_{++}} \leq\leq 10^{-8}$

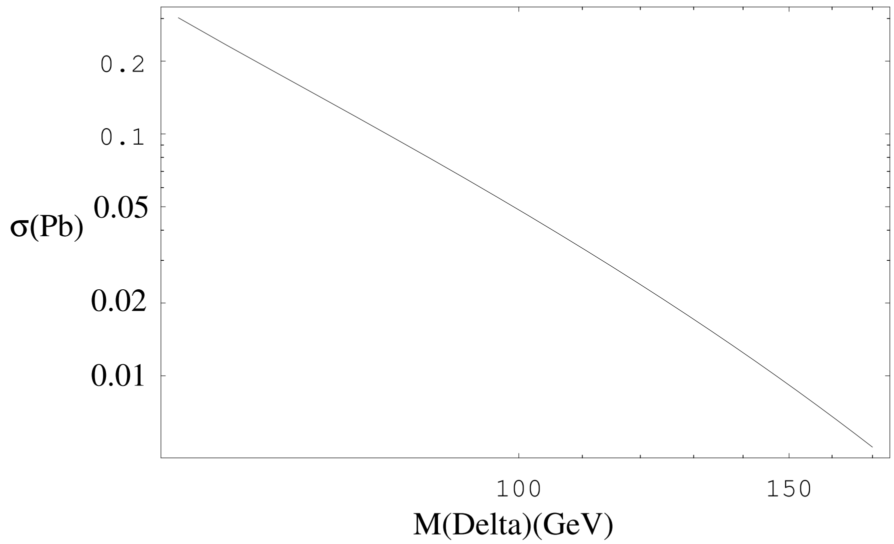


Figure 19: Production cross section of Δ^{++} Higgs bosons in Tevatron.

SUSY $\rightarrow$ doubly charged fermions

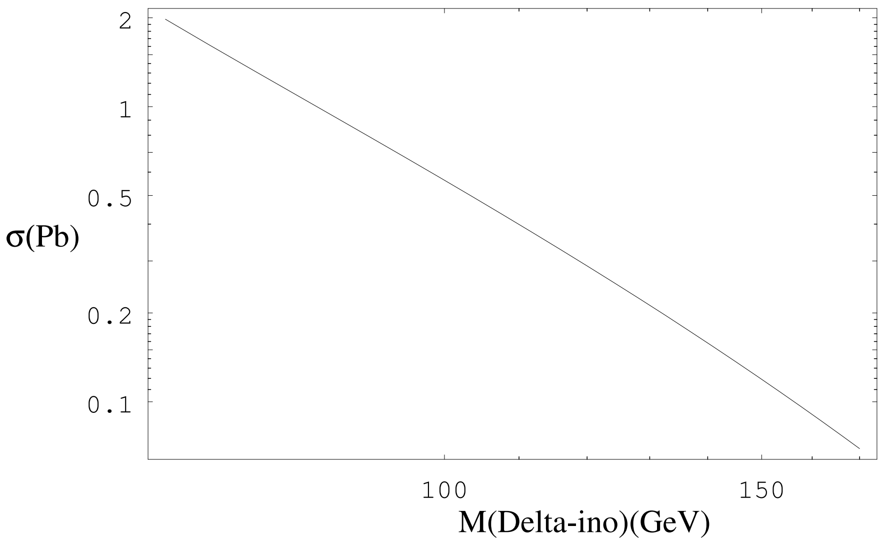


Figure 20: Production cross section for doubly charged Higgsinos at Tevatron.

☞ $\tilde{\Delta}^{++} \rightarrow \mu^+ + \tilde{\mu}^+ \rightarrow \mu^+\mu^+ +$ **missing E.**

Neutrino mass and neutron-anti-neutron oscillation

☞ **Seesaw requires Majorana mass for RH neutrinos i.e. $\Delta L = 2$.**

But the true symmetry is $(B-L)$; so $\Delta L = 2$ implies $\Delta(B-L) = 2$.

For processes involving hadrons, $\Delta(B-) = 2$ implies $\Delta B = 2$ or $N - \bar{N}$ oscillation..

Two questions are:

(i) How to search for $N - \bar{N}$ oscillation ?

(ii) Are there any decent theories where $N - \bar{N}$ oscillation time is measurable ?

Experimental search for $\tau_{N-\bar{N}}$

☞ **Phenomenology of $N - \bar{N}$**

$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix} N \\ \bar{N} \end{pmatrix} = \begin{pmatrix} E_n & \delta m \\ \delta m & E_{\bar{n}} \end{pmatrix} \begin{pmatrix} N \\ \bar{N} \end{pmatrix} \tag{1}$$

$P_{N\to\bar{N}} \sim \left(\frac{\delta m}{\Delta E_n}\right)^2 sin^2 \Delta E_n t$

☞ **Two cases**

➢ Case (i): $\Delta E_n t \ll 1$: $P_{N\to\bar{N}} \sim (\delta m \cdot t)^2 \equiv \left(\frac{t}{\tau_{N-\bar{N}}}\right)^2$ corresponds to free neutron oscillation;

➢ Case (i): $\Delta E_n \cdot t \gg 1$: $P_{N\to\bar{N}} \sim \frac{1}{2}\left(\frac{\delta m}{\Delta E_n}\right)^2$ corresponds to bound neutrons.

Curious coincidence

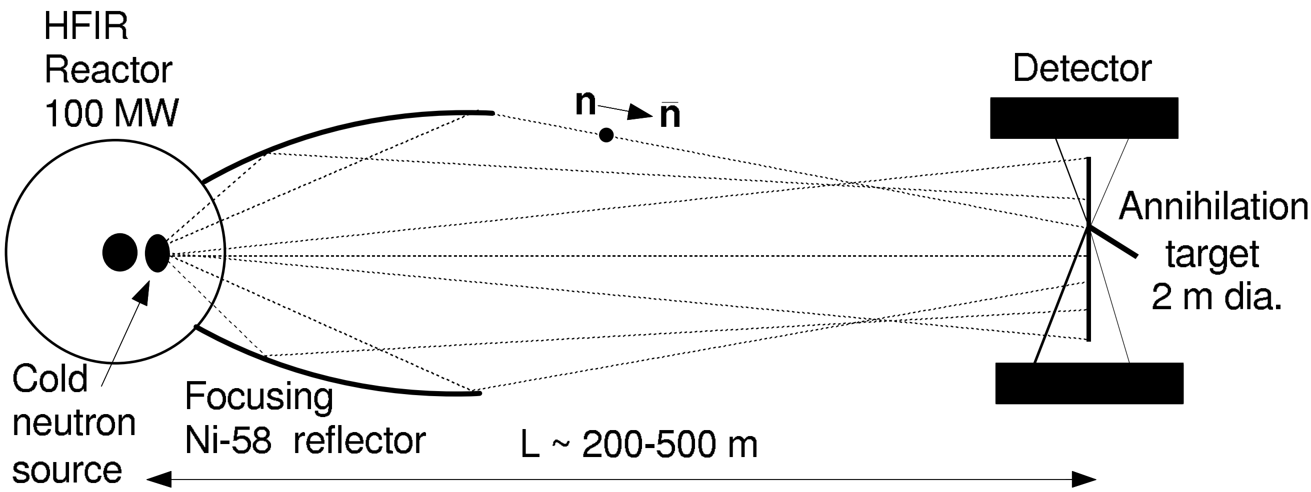
☞ **Stability of Nuclei to $\Delta B \neq 0$ should give a limit on $\tau_{N-\bar{N}}$:**

To see what this is, note that for nuclei,
$E_N - E_{\bar{N}} \sim 100$ **MeV; so**

$\tau_{Nucl.} \sim \left(\frac{\delta m}{2\Delta E_n}\right)^{-2} 10^{-23}$ **sec. This should be** $\geq 10^{32}$ **yrs.**
$\rightarrow \delta m \leq 10^{-29}$ **MeV or** $\tau_{N-\bar{N}} \geq 10^{8}$ **sec.**

We will see that present reactor neutron fluxes are precisely in the right range to probe these values of $\tau_{N-\bar{N}}$.

Reactor Search Expt. set-up: ILL (1994)



☞ **Key Formula for doing an expt.**

# of events $= N \left(\frac{t}{\tau_{N-\bar{N}}}\right)^2 \times T \sim 1$

where N **= reactor flux;** $v_N t$**= distance to detector;** T **running time.**

Feasibility of further improvement

☞ **Maximum available reactor fluxes (100 MW reactor)** $\sim 10^{13} - 10^{14}$ **N/cm^2 sec.; for** $t = 0.1$ **sec. and** $T \sim 3$ **years can yield a limit of** 10^{10} **sec.**

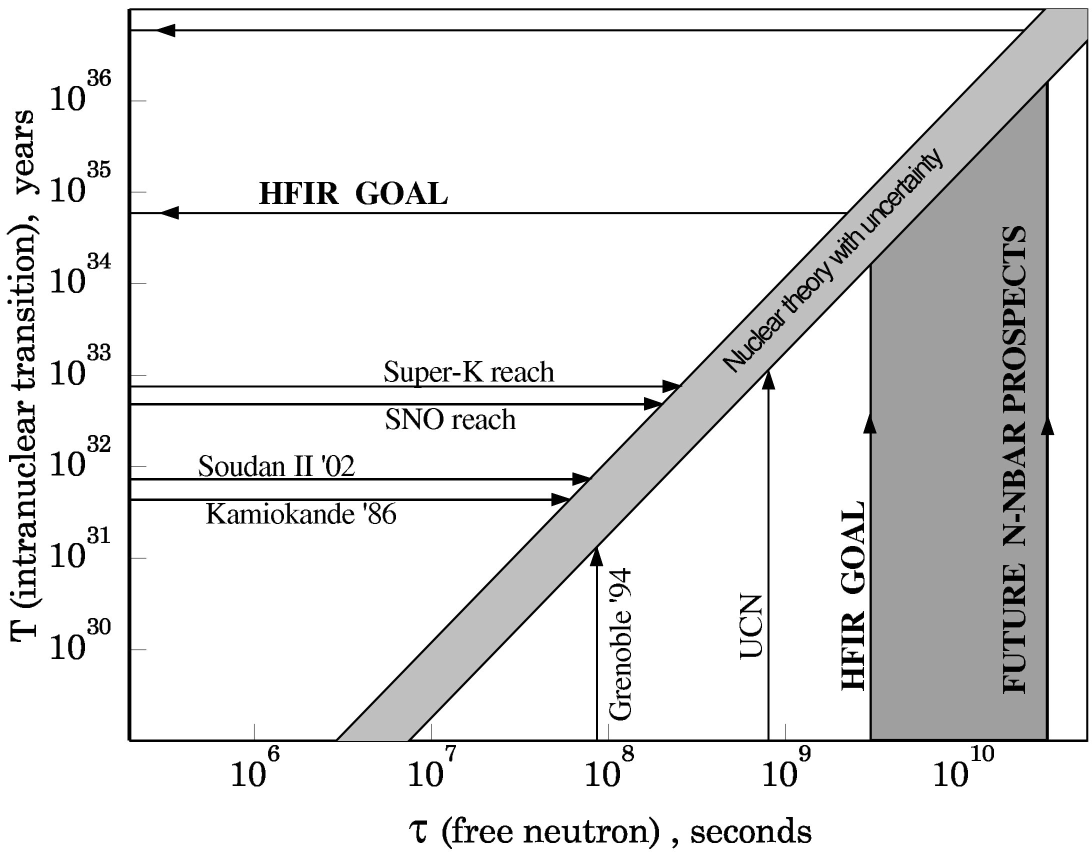
Need to ensure that there is a magnetic shielding to the level of 10^{-5} **Gauss which is achieved by** μ**-metal shielding.**

Present limit from ILL, 1994- Baldoceolin et al.: $\tau_{N-\bar{N}} \geq 8.6 \times 10^7$ **sec.**

New search effort and proposal by Y. Kamyshkov, M. Snow, A. Young et al., hep-ex/0211006 but no concrete site yet.

Comparison of free-neutron and bound-neutron methods

☞



Expectations for $\tau_{N-\bar{N}}$ in SUSY seesaw models

☞ **Operator analysis**

No Supersymmetry and SM field content:
Effective operator: $\mathcal{O}_{\Delta B=2} = \frac{u^c d^c d^c u^c d^c d^c}{M^5}$;

$\delta m_{N\bar{N}} \sim \mathcal{O}\Lambda^6_{QCD}$
and
$\delta m_{N-\bar{N}} = \frac{1}{\tau_{N\bar{N}}}$ **(h-bar=1);**

Present limit of $\tau_{N\bar{N}} \geq 10^8$ **sec** $\rightarrow$
$M \sim 10^{5.5}$ **TeV.**

Does it mean that $N - \bar{N}$ **can only probe 100 TeV range scales ?**
Yes, if there is no supersymmetry; but things change drastically, if there is SUSY

SUSY and effective operator for $N - \bar{N}$

☞ **Supersymmetry introduces a new $\Delta B = 2$ operator that has lower dimension ($u^c d^c \tilde{d}^c \tilde{u}^c \tilde{d}^c \tilde{d}^c / M^3$) than the nonsusy case.**

If the TeV scale theory has a scalar field of type $\Delta_{u^c u^c}$, then the effective operator is: $\Delta_{u^c u^c} d^c d^c \tilde{d}^c \tilde{d}^c / M^2$.

The combination of these two effects reduce the dependence on M_{seesaw} making $N - \bar{N}$ observable even for high seesaw scale$\sim 10^{11}$ GeV.

Seesaw, $N - \bar{N}$ connection

☞ **Neutrino mass is pure L-violation whereas $N - \bar{N}$ is baryon violating; how could they be related in an actual theory ?**

The connection is there once quarks and leptons are unified e.g. in a model with Pati-Salam $SU(4)_c$ or if there are interactions that connect quarks to leptons (unlike in the standard model).

•: $SU(4)_c$ **example:**

$$F_{L,R} \equiv \begin{pmatrix} u & u & u & \nu \\ d & d & d & e \end{pmatrix}_{L,R}.$$

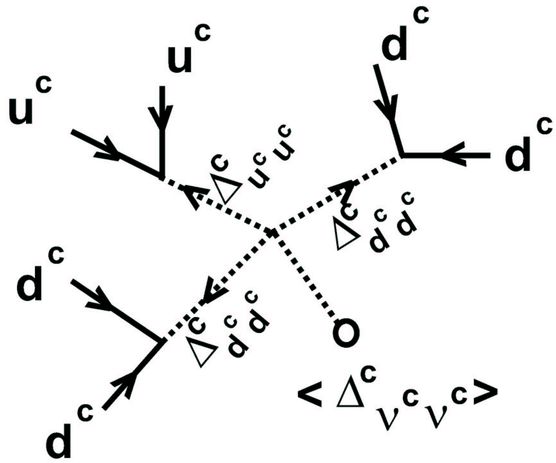
Recall seesaw mass arises from a B-L=2 multiplet which has quantum number of type Δ_{ll}.

$$\Delta_R(1,3,+2) \equiv \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$

In a quark-lepton unified theory, this has companions of type- Δ_{ql} and Δ_{qq};
The Feynman diagram responsible for $N - \bar{N}$ oscillation next page:

Diagram for $N - \bar{N}$ oscillation in $SU(4)_c$ models

☞



- yields $\tau_{N-\bar{N}} \propto M^5_{\Delta_{qq}}$; **For $M_{\Delta_{qq}} = 100$ TeV, $\tau_{N-\bar{N}} \sim 10^7 - 10^8$ sec. which is measurable**

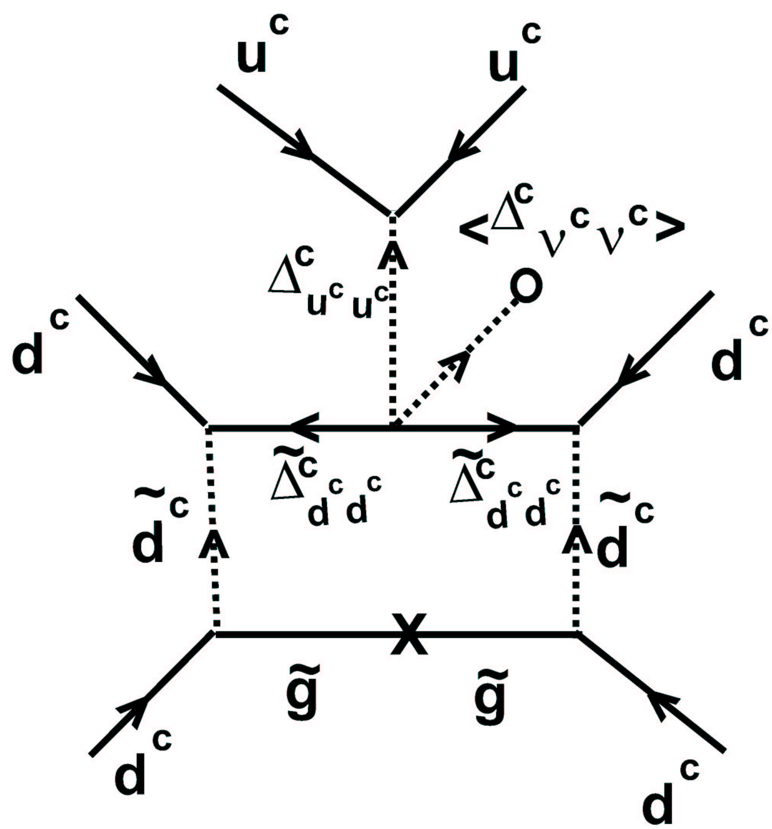
Since $M_{\Delta_{qq}} \sim M_{seesaw}$, in a non-supersymmetric theories, $N - \bar{N}$ is observable in the low scale (¡ 100 TeV) models.

Supersymmetric enhancement of $N - \bar{N}$

☞ **In SUSY $SU(4)_c$ models, some diquarks $\Delta_{u^c u^c}$ become 100 GeV scale even with high seesaw scale due to large accidental symmetries;**
e.g. suppose there is a B-L=2 triplet under SU(2).
$W = S(\Delta\bar{\Delta} - M^2)$
has a global symmetry $SU(3, c)$; when SU(2) breaks down, more Goldstone bosons appear !! This effect gets magnified when there is $SU(4)_c$.

SUSY diagrams for $N - \bar{N}$

☞ **New diagrams for $N - \bar{N}$ appear and weaken the power dependence on the seesaw scale to M^{-2} from M^{-5}.**



☞ $G_{N-\bar{N}} \simeq \frac{f_{11}^3}{\lambda^2 M_{seesaw}^2 v_{wk}^3}$
$M_{seesaw} \sim 10^{11}$ **GeV, typical** f, λ**,** $\tau_{N-\bar{N}} \sim 10^{10}$ **sec.**

diquarks are observable at LHC.

☞ $\Delta^*_{u^c u^c} \rightarrow tt$ **is the interesting mode since** t **quarks are "easier" to observe at LHC.**
Signature: $\Delta^*_{u^c u^c} \rightarrow tt, \quad tc, ...$

$tt \rightarrow jj\ell + missingE$

References for $N-\bar{N}$ oscillation

Nonsusy $SU(4)_c$ model: Marshak, RNM, PRL, 44 1316 (1980)

SUSY $SU(4)_c$:
(Chacko, RNM, 1999); Dutta, Mimura and RNM, (2005)

Babu, Nasri and RNM, PRL (2007).

Conclusions

☞ **Many interesting hints of new physics in neutrino data**
Detailed nature of this new physics is still work in progress, although some things are becoming clear:

- Almost sure: Seesaw mechanism and right handed neutrinos!;
- Seesaw scale still not completely clear-although the case for SO(10) like theory quite compelling
- Also strong hints of possible family symmetries e.g.$\mu - \tau$ exchange or S_3 symmetry to explain tri-bi-maximal mixing in data.
- Not clear whether it is symmetries or a dynamical mechanism doing large neutrino mixings (as in SO(10) models) !! Far deviations from maximality will point to a dynamical mechanism.
- searching for CP violation in the leptonic sector will clarify our understanding of one of the fundamental mysteries of cosmology i.e. origin of matter;
- we must be alert to any sterile neutrino effects.

Future is bright

☞ **New Era of Precision Neutrino Measurement Science –PNMS era– about to be lunched will determine neutrinos' Majorana nature, θ_{13}, mass ordering and create a new road-map for flavor physics beyond the standard model.**

Extra stuff

☞ Limit on W_R mass

Beall, Bender, Soni (82);,

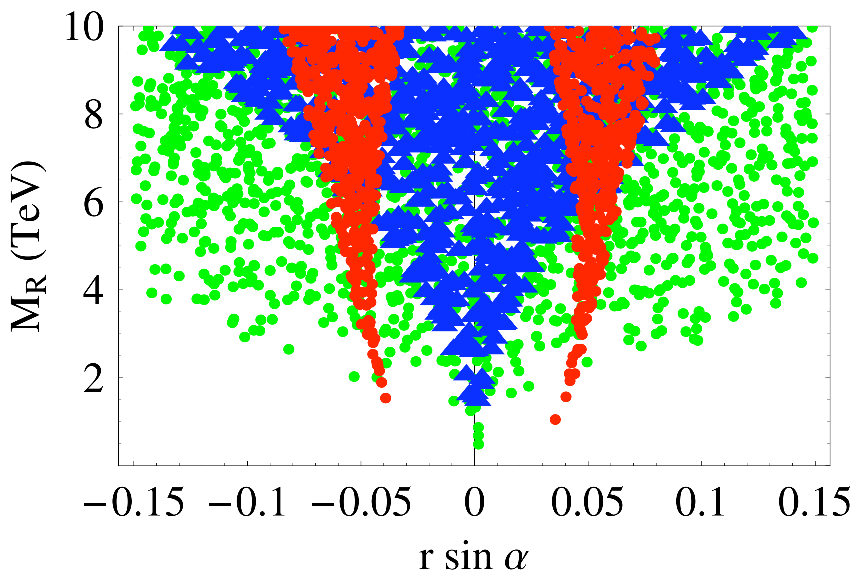


Figure 21: **Lower limit on W_R in the minimal non-supersymmetric LR model. Red points from ϵ_K and Green and Blue points from d_n for different values of $W_L - W_R$ mixing. From a recent analysis by Zhang, An, Ji, RNM (2007)**

☞ which gives a lower limit of 2.5 TeV in the minimal LR models with no supersymmetry.

Include SUSY or expand the Higgs sector, the limit goes Sub-TeV.